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# NOVEL APPARATUS AND TECHNIQUE FOR MEASURING RR RESISTIVITY OF TUBE COATINGS AT CRYOGENIC TEMPERATURES*

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*Abstract*

A unique apparatus for measuring RF resistivity of tubes and coated tubes at cryogenic temperatures is operational at BNL, which to our knowledge is the first of its kind. A folded quarter wave resonator structure of 300 mm length accesses a wide range of frequencies. The structure is cooled in liquid He bath at 4 K. All internal resonator components (except for test samples and antennae) were fabricated out of superconducting materials. Consequently, when the resonator is cooled, the bulk of the losses are due to the copper coating. The RF resistivity is determined from weakly-coupled Q measurements, since for a fixed geometry the quality factor of a resonant mode is proportional to the RF surface resistance. The RF input loop and the output signal antenna are adjustable when cold via bellows to control matching to each cavity mode. The Q values of 10 resonant modes between 180 and 2500 MHz are deduced from the bandwidth of the S21 response Network Analyzer measurements. CST MicroWave Studio is used to calculate the RF surface resistance of the samples from the Q measured for each mode. Additionally, DC resistivity of the copper coated was measured. Resistivity results of solid Cu tube, 2, 5, and 10 µm Cu coated 316LN stainless steel RHIC beam tubes at room temperature as well as at cryogenic temperatures are presented.

## INTRODUCTION

High wall resistivity in accelerators can result in unacceptable levels of ohmic heating or to resistive wall induced beam instabilities [1]. This is a concern for the Relativistic Heavy Ion Collider (RHIC) machine, and even a larger concern future RHIC upgrades including the electron ion collider eRHIC as its vacuum chamber in the cold arcs is made from relatively high resistivity 316LN stainless steel. This effect can be greatly reduced by coating the accelerator vacuum chamber with Oxygen-Free High Conductivity (OFHC) copper, which conductivity is three orders [2,3] of magnitude larger than 316LN stainless steel at 4 K. Previously, it was demonstrated [4] that deposition of even 5 µm of copper on RHIC tubing can result in room temperature conductivity, which is very close to solid copper. Room-temperature RF resistivity measurements [5, 6] were performed on 32 cm long RHIC stainless steel tubes coated with 2 µm, 5 µm, and 10 µm, thick OFHC with a folded quarter wave resonator structure. Q values were measured for eight resonant modes in the range of 180 MHz to 2 GHz, from which conductivity was deduced. Those measurements [5, 6] indicated that for the later 2 coatings conductivity was about 5 x $10^7$ Siemens/meter or about 84% of pure copper. Since joints and connectors reduce the experimentally measured Q, the conductivity value of coatings may be even closer to pure solid copper. Additional details can be found in Ref. [5, 6]. Computations indicate [7] that 10 µm of copper should be acceptable for even the most extreme future scenarios.

However, low temperature Physical Vapor Deposition (PVD) of copper on stainless steel tubes does not have the same conductivity as copper tubing at cryogenic temperatures. The reason is that straightforward deposition of thick films tends to result in coatings with lattice defects and impurities, which at cryogenic temperature severely degrades conductivity. Even though this is covered in a number of books [8-12], clear evidence is not found in research papers. Understanding of these phenomena is based on the following: in the case of room temperature copper, conductivity is dominated by conduction band electrons, while at cryogenic temperatures, lattice defects and impurities result in large conductivity reduction. Physically, electrons are scattered off lattice defects, small grains and impurities, causing significant conductivity degradation. Straightforward deposition of thick films [13] tends to result in coatings with lattice defects and impurities, and columnar crystal and other microstructures [14] are often observed in conventional, low temperature physical vapor deposition of thick films.

Since RHIC and its future upgrades including eRHIC have large sections that operate at cryogenic temperatures, any copper coating has to have crystalline structure and must be free of impurities. Additionally, the coating RF surface resistance must be measured at cryogenic temperature. Consequently, two R&D programs are being pursued. To reduce coating lattice imperfections, we utilize energetic ions for Ion Assisted Deposition (IAD).

In parallel, a device for measuring the RF surface resistance of copper coated stainless-steel tubes at cryogenic temperatures was developed. The technique is based on Q measurements, from which the RF surface resistance for selected modes is to be determined, since for a fixed geometry the quality factor of a resonant cavity is proportional to the inverse of the real part of the surface impedance. Although variations on that technique can have multiple applications, the focus of this effort is to develop a device and

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technique for measuring and optimizing conductivity at cryogenic temperatures of RHIC tubing coated with OFHC. With this device, Cu coating of RHIC tubes is to be optimized by iterative processes. Before embarking on a large task like copper coating a section of RHIC, it is prudent to test coating properties (especially conductivity) at cryogenic temperatures on a smaller scale. Since there are no metrics to determine coating resistivity [16] other than measurements, it is judicious to optimize coating and perform these measurements on small tubing samples before coating a long tube.

## THE RESONANT CAVITY

The device is basically a cryogenic resonant cavity; it consists of a folded quarter wave resonator structure that comes immersed into a cryogenic bath to measure the resistivity of coatings. The RF surface resistance of samples is to be deduced from the Q value of selected resonant modes between 180 and 2000 MHz, since for a fixed geometry the quality factor of a resonant cavity is proportional to the inverse of the real part of the surface impedance. Design is based on making the resonator structure out of niobium such that the test sample copper coated stainless steel, is the most lossy material. Design and device are shown in Fig. 1 and 2.

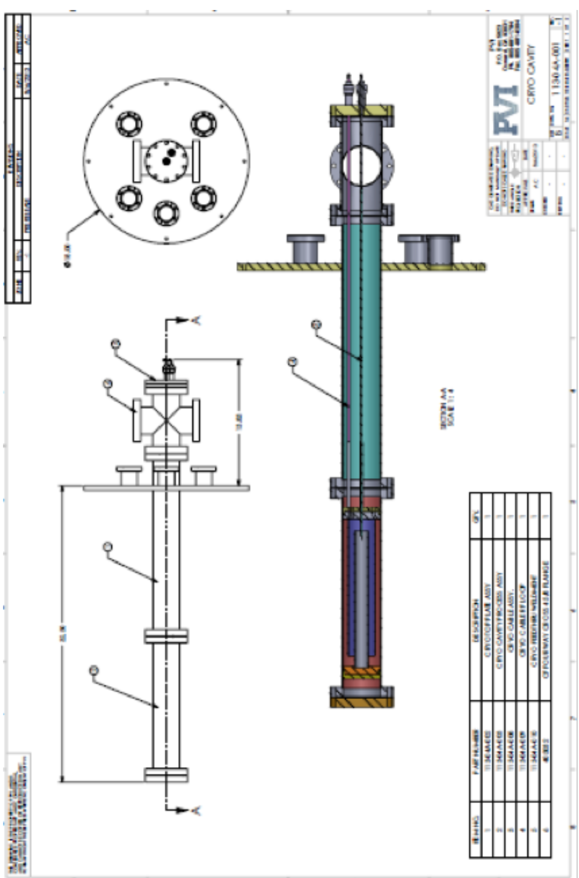

Figure 1: Cryogenic resonator design.

Design of the folded quarter wave resonator structure mounted flange includes drives for adjustment of signal launch and pickup to facilitate measurement of multiple frequencies during one cooldown. Consequently, the designed device features adjustable in-situ, at cryogenic temperatures, signal input and output couplers for enabling multiple frequency measurements in each cool-down. The input coupler is small and adjustable to provide weak coupling even at the top frequencies; both input coupler and output coupler are adjustable. The RF input loop can be in-situ rotated by a rotary ferrofluidic drive, which has ± $180^0$ rotation capability, while the output signal coupler has 4-inch linear motion facilitated by bellows.

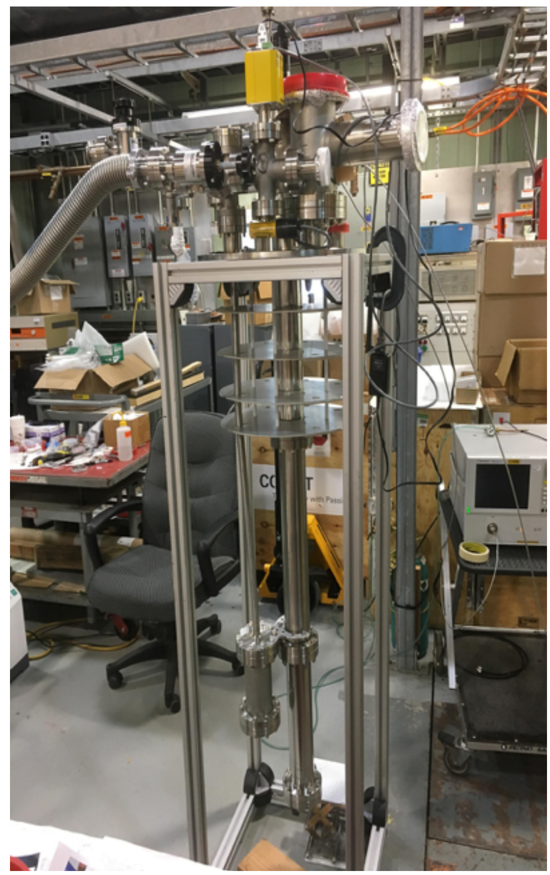

Figure 2 The BNL assembled cryogenic resonator.

## TESULTS

Room temperature conductivity measurements [4-6] of RHIC tubes coated with 5 μm and 10 μm thick OFHC showed conductivity that was 84% of the theoretical conductivity of copper. The real value may be closer to pure copper, since joints and connectors might have reduced the experimentally measured Q from which conductivity was calculated.

Next stainless steel RHIC tubes coated with 5 μm and 10μm thick copper were measured at 4K with the cryogenic resonator shown in Fig. 2. In a RHIC tube coated with 10 μm thick copper, which might have had some contaminates, conductivity enhancement at 4K was only a factor of 1.2. After removing contamination sources, conductivity enhancement at 4K of RHIC tubes coated with both 10 μm and 5 μm thick copper coating was enhanced by a

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factor of 2.3 of its conductivity at room temperature; i.e. conductivity of 2.3 x 5.7 x $10^7$ Siemens/meter, which is within a factor of 2 of what is needed for eRHIC!

Figure 3 is a summary of RF surface resistance as determined from Q measurements of a thin copper tube, 5 μm and 10 μm stainless steel copper coated tubes as function of RF frequency.

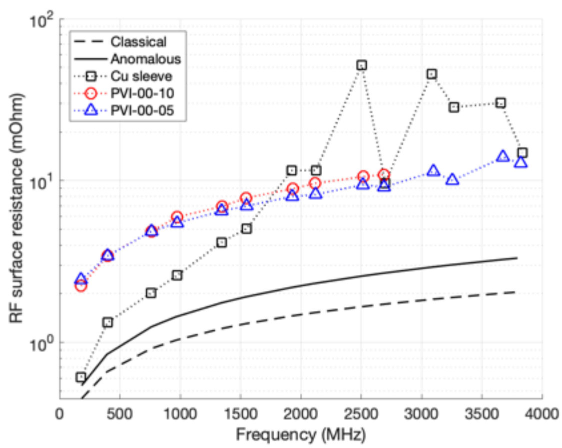


Figure 3: RF coating resistance as inferred from cryogenic resonant measurements of Cu sleeve and RHIC tubing with 10 μm and 5 μm coatings.

Dashed and solid lines are calculated RF surface resistance using classical and anomalous skin effect models respectively. Black squares indicate measured resistance of a copper sleeve, while red circles and blue triangles are measurements of 10 μm (PVI-00-10) and 5 μm (PVI-00-05) thick copper coatings respectively. Discrepancy displayed at high frequencies for copper sleeve data was also previously observed in copper coated stainless-steel samples. The problem was associated to the test device and was solved for the measurement of the PVI-00-10 and PVI-00-05 samples. The copper sleeve will be re-measured.

## DISCUSSION

To our knowledge, the cryogenic resonator described in this paper is the first of its kind as it facilitates determining RF conductivity of beam pipe tubes at cryogenic temperatures over a large range of frequencies in a single cool-down. Although a number of good measurements were performed, some additional studies are needed; e.g. re-measuring the copper sleeve. Measurements were studied considering insufficient field decay in copper layer that ends up damping in stainless steel. Further studies should consider contribution of anomalous skin effect and surface roughness – relevant at high frequencies – and especially performing measurements on a niobium tube in order to properly account for contributions of joints and connectors to measured resistance. Although it is work in progress, the device appears to function well.

## ACKNOWLEDGEMENTS

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